

*'Pebble Bed Modular Reactor
Fuel Qualification
Test Program'*

*Presented to the NRC
March 28, 2002
Rockville, MD*

- ◆ Describe the Proposed US Pebble Bed Modular Reactor (PBMR) Fuel Qualification Test Program
- ◆ Describe the Proposed International PBMR Fuel Qualification Test Program
- ◆ Discuss the Role of Existing International Fuel Test Data in Establishing the Integrated (i.e. US and International) Fuel Qualification Test Program

- ◆ PBMR Fuel Qualification Testing and Relationship to Licensing Basis
- ◆ Production of PBMR Fuel
- ◆ Existing International Fuel Test Data
- ◆ PBMR Fuel Qualification Testing
 - ◆ Fuel Failure Mechanisms
 - ◆ Fuel Testing Under Normal Conditions
 - ◆ Fuel Testing Under Accident Conditions
 - ◆ Post Irradiation Exams (PIEs)

- ◆ Combined License (i.e., COL) Application
- ◆ Fuel Performance Requirements Will Be Reflected in Licensing Basis
- ◆ Design and Fabrication of PBMR Fuel Based Directly on German Experience
 - ◆ Proven Design, Processes and Performance
- ◆ Testing to Confirm Compliance with Licensing Basis Versus Proof of Concept

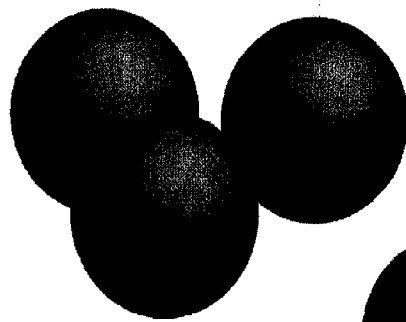
- ◆ Proof of Concept Demonstrated by Existing Large Body of International Fuel Test Data
- ◆ PBMR Fuel Qualification Test Program Will Be Confirmatory in Nature
- ◆ Test Results Used to Confirm Compliance of Production Fuel with PBMR Licensing Basis Performance Requirements
- ◆ Test Results Not Required for Approval of COL

- ◆ Testing to Include Fuel from Large-Scale Production Facility
- ◆ Initial Core Load Manufactured Prior to Completion of Entire Test Program
- ◆ Initial Test Program Results to Support Initial Plant Operation

- ◆ PBMR to Manufacture High Quality Fuel
 - ◆ Comparable to German Fuel (AVR 21-2 Reference)
 - ◆ Design Specifications
 - ◆ Manufacturing Processes
 - ◆ Materials
 - ◆ Quality Controls
- ◆ High Quality Fuel to Ensure Retention of Fission Products
 - ◆ Normal Operating Conditions
 - ◆ Accident Conditions

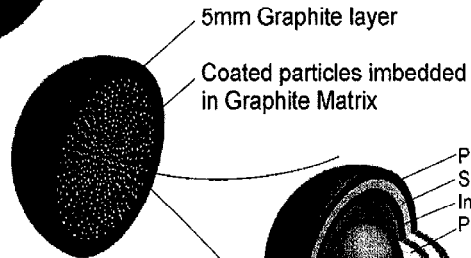
- ◆ Well Defined Quality Control (QC)
 - ◆ QC on Incoming Feed Materials
 - ◆ QC on Uncoated UO_2 Kernels
 - ◆ QC During Particle Coating Process
 - ◆ QC on Fuel Spheres
- ◆ Manufacturing Processes and QC - Key to Meeting PBMR Fuel Performance Requirements

FUEL ELEMENT DESIGN FOR PBMR

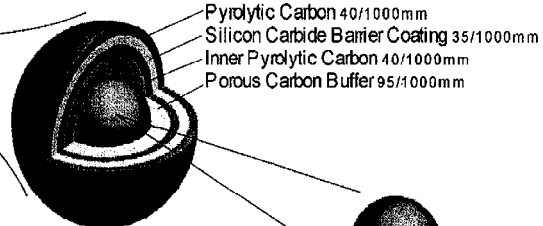


Dia. 60mm

Fuel Sphere



Section



Dia. 0,92mm

TRISO
Coated Particle



Dia. 0,5mm
Uranium Dioxide

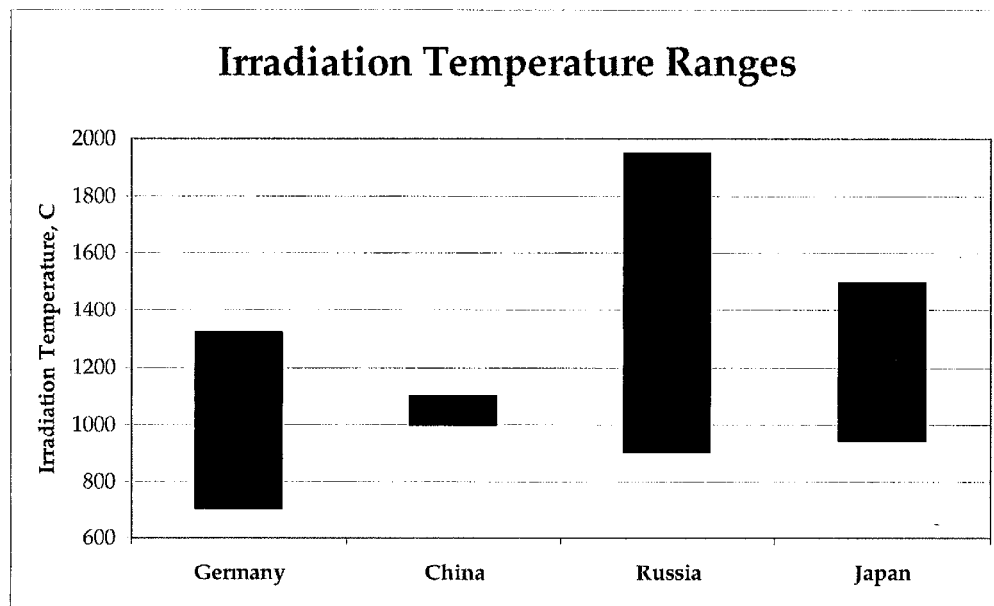
Fuel Kernel

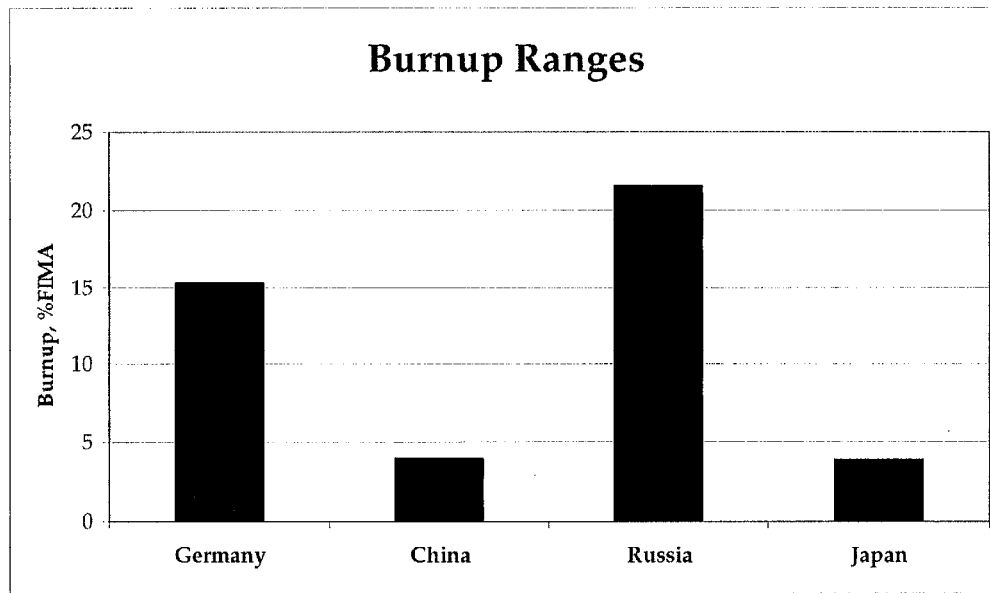
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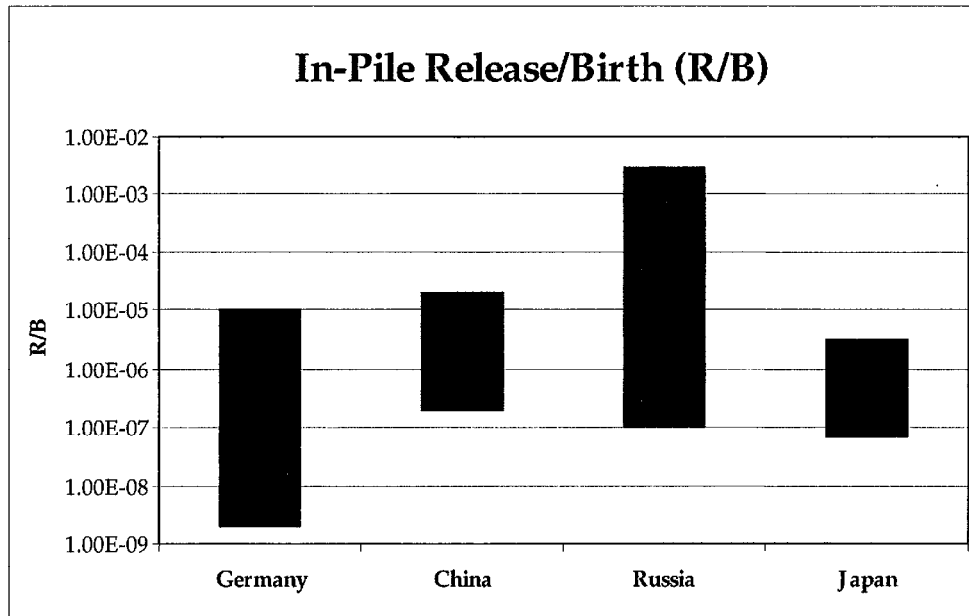
- ◆ Coated Particle Fuel Under Development for Over 40 Years
- ◆ Last 25 Years Saw Focus on UO_2 TRISO Fuel, Initially in Germany, Also Russia, Japan, China
- ◆ Extensive International Information Exchange Documented in IAEA-TECDOC-978, 'Fuel Performance and Fission Product Behaviour in Gas Cooled Reactors'
- ◆ Design of PBMR Particle Fuel Based Directly on the Optimized German Design
- ◆ Test Data Available Covering Both Normal Operation and Accident Conditions

Performance Under Normal Operation

- ◆ Extensive UO₂ TRISO Irradiation Programs Conducted in Germany, Russia, Japan
- ◆ Combined Temperature, Fluence and Burnup Ranges Envelope PBMR Conditions
- ◆ Proof of Concept, Including Demonstration of Performance Margins, Provided by Existing International Data

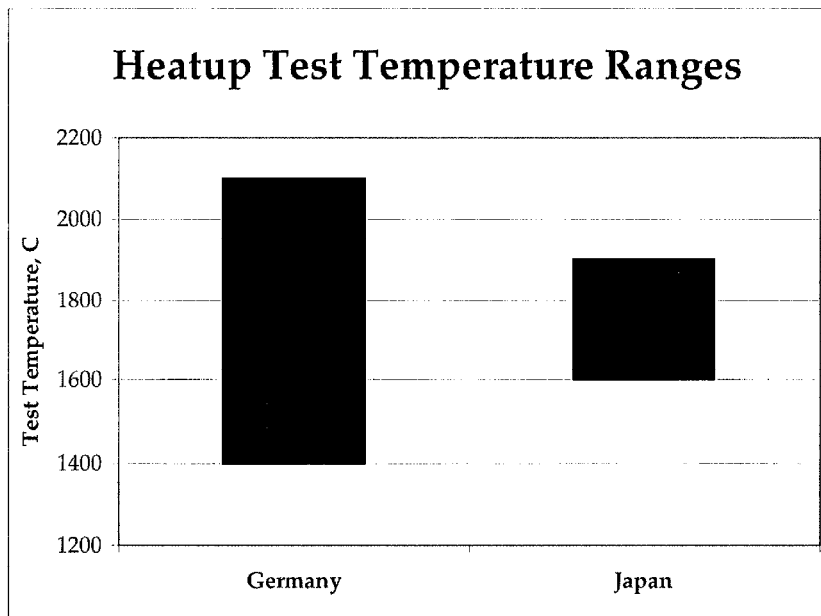


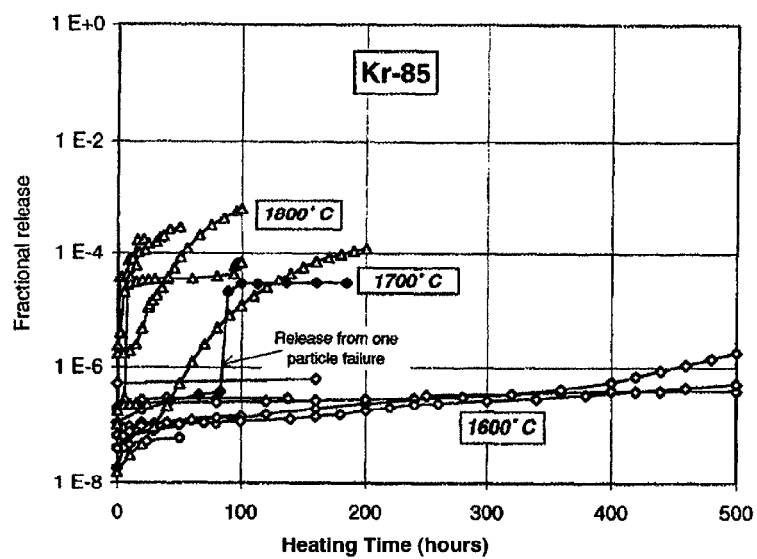




Performance Under Accident Conditions

- ◆ Existing International Data Are Sufficient To:
 - ◆ Characterize Failure Thresholds and Mechanisms
 - ◆ Quantify Margins for Heatup Events
- ◆ Irradiated UO_2 Fuel Heatup Testing Explored Temperature Ranges Far Exceeding the Expected PBMR Maximum Conditions





Performance Under Accident Conditions

- ◆ Oxidation Testing
 - ◆ Air and Water Ingress Conditions
 - ◆ High Degree of Retention of Fission Products
- ◆ Reactivity Transient Testing
 - ◆ Pulsed and Sustained Overpower Conditions
 - ◆ Large (>10x) Overpower Capability

- ◆ Overview
- ◆ Fuel Failure Mechanisms/Key Variables
- ◆ Testing – Normal Conditions
- ◆ Testing – Accident Conditions
- ◆ Post Irradiation Examination (PIE)

- ◆ Objective - Confirm that PBMR Production Fuel Performance is Consistent With Existing Test Data and Will Therefore Meet the Licensing Basis Performance Requirements
- ◆ Integrated International Test Program
 - ◆ Republic of South Africa (RSA)
 - ◆ Russia
 - ◆ US
- ◆ Test Program to Meet Applicable NRC QA Requirements

- ◆ Elements of the Program Conducted Internationally
 - ◆ Safari Reactor – RSA
 - ◆ IVV-2M Reactor – Russia
 - ◆ Advanced Test Reactor (ATR) – US
- ◆ Fuel to be Tested
 - ◆ Archived German Fuel – AVR 21-2
 - ◆ PBMR Pre-Production Fuel
 - ◆ PBMR Production Fuel

- ◆ Test Conditions Are a Function of PBMR Expected Operating Envelope and Accident Conditions
- ◆ Fuel Irradiation Testing
 - ◆ Maximum Temperature Under Normal Operation
 - ◆ Temperature Cycles
 - ◆ Average PBMR Burnup ~ 8.8% FIMA (80 GWd/MtU)
 - ◆ Average Fluence ~ 2×10^{25} n/M²
 - ◆ Slightly Accelerated Irradiations
- ◆ Safety (Heatup) Testing
 - ◆ 1600° C

- ◆ Large Air or Water Ingress and Large Reactivity Insertion Events Are Low Probability Events
 - ◆ Not Expected to Be PBMR Licensing Basis Events
 - ◆ No Oxidation or Reactivity Insertion Fuel Qualification Testing Planned

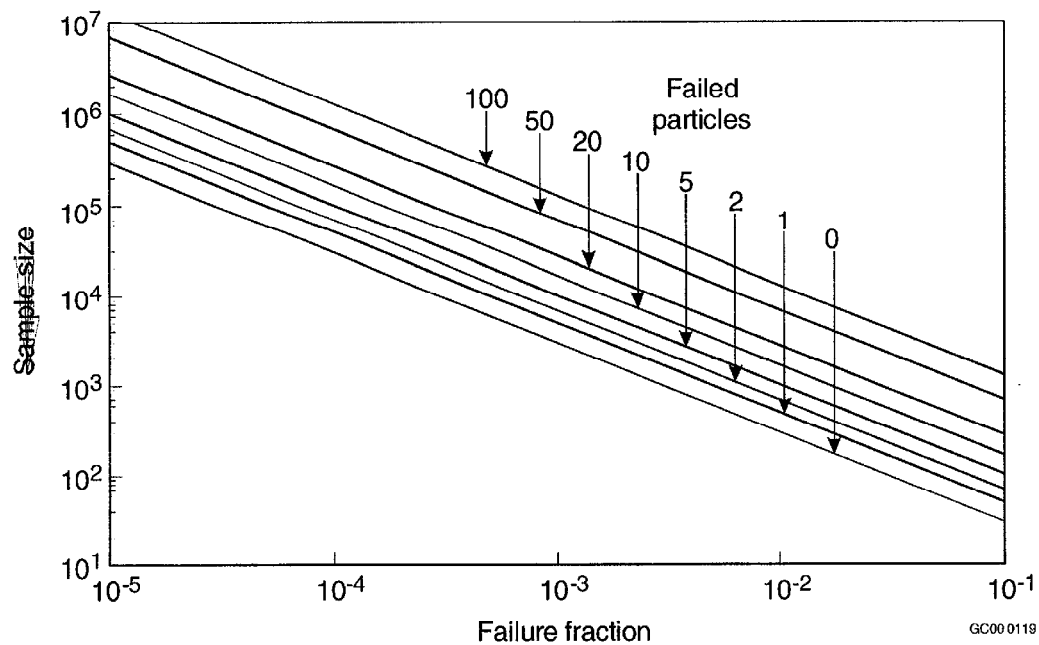
Type of Testing	Type of Fuel or Nature of Test	Objectives/Comments
Pre-Demonstration Irradiations	Pre-production fuel in RSA and Russia Archived German fuel in US	Use these tests to shakedown facilities. Irradiate German fuel to test influence of PBMR operating temperature
Demonstration Irradiations	Production fuel. Statistically significant quantities under irradiation in Russia and RSA	Demonstrate fuel performance under normal operating conditions (temperature, fast fluence and burnup).
Irradiation Margin Testing	Temperature, burnup and fluence margin testing in US	Explore behavior outside of normal operating envelope. Supplement statistical database
Safety Testing	Traditional isothermal heatup testing. Russia and RSA testing of safety envelope.	Demonstrate fuel performance under accident conditions. Statistical quantity of fuel at 1600°C. Burnup and temperature are key variables
Safety Margin Testing	US testing will explore beyond the safety envelope (margin)	Explore behavior at and outside of the safety envelope (test at and beyond 1600°C). Supplement statistical database
Post Irradiation Examination	After irradiation and safety tests	Characterize the state of the fuel after irradiation and safety testing.

- ◆ Overpressure
- ◆ Pyrocarbon Cracking
- ◆ Pyrocarbon Creep
- ◆ Kernel Migration
- ◆ Fission Product Attack of Silicon Carbide (SiC)
- ◆ SiC Thermal Decomposition
- ◆ Enhanced SiC Permeability
- ◆ As-Manufactured Defects

- ◆ Temperature
- ◆ Fluence (> 0.1 MeV)
- ◆ Burnup
- ◆ Temperature Gradient

- ◆ Operating Condition Parameters and Failure Mechanisms Are Well Known
 - ◆ Testing of a Broad Range of Fuel Designs
 - ◆ Extreme Service Conditions
- ◆ Excellent PBMR Fuel Performance Expected
 - ◆ Service Conditions Within German Envelope
 - ◆ German Experience - Mechanisms Are Not Active
- ◆ As-Manufactured Defective Particles Only Likely Source of Failures
- ◆ As-Manufactured Defects to Be Maintained Very Low

- ◆ German Fuel - Very Low Failure Rates (Zero Failures in ~280,000 Particles)
- ◆ Confirmation of Low Failure Rates at 95% Confidence Requires a Considerable Quantity of Particles Tested
- ◆ Statistically Significant Number of Particles to Be Tested in Russia
 - ◆ Irradiation
 - ◆ Safety Tests @ 1600° C
- ◆ US Testing Will Supplement Russian Statistics



Pre-Demonstration Testing

Facility Location	# Pebbles	Temperature	Burnup (% FIMA)	Fast Fluence (*10 ²⁵ n/m ²)	Comments
Pre-production Fuel					
South Africa	4	High	9%	2	Constant temperature irradiation
Russia	4	Temperature cycles	11%	2	Multiple temperature cycles – 1/3 cycle @ Lower, 2/3 cycle @ Higher
Archived German Fuel					
US	6	High	9% to 11%	2.1 to 4	Constant temperature irradiation

FIMA = Fissions per Initial Metal Atoms

Demonstration Testing

Facility Location	# Pebbles	Temperature	Burnup (% FIMA)	Fast Fluence (*10 ²⁵ n/m ²)	Comments
Production Fuel - Demonstration Portion of Qualification Program					
South Africa	4	High	4%	1	Constant temperature irradiation
	4	High	6%	1.6	Constant temperature irradiation
Russia	12	Temperature cycles	11%	2.8	Multiple temperature cycles – 1/3 cycle @ Lower, 2/3 cycle @ Higher. Pressurized Loss of Forced Cooling simulation for several pebbles at end of irradiation. Statistically significant quantity of fuel.

Demonstration Margin Testing

Facility Location	# Pebbles	Temperature	Burnup (% FIMA)	Fast Fluence (*10 ²⁵ n/m ²)	Comments
Production Fuel - Margin Portion of Qualification Program					
US	2	High + 100°C	11%	~ 6 - 8	Constant temperature irradiation. High temperature margin test
	2	High	11%	~ 6 - 8	Constant temperature irradiation. Fluence margin test
	6 - 8	High	11%	~ 6 - 8	Constant temperature irradiation. Feedstock for safety margin testing. Supplement Russian statistics.
	2 - 4	High	~ 5%	~ 6	Constant temperature irradiation. Feedstock for margin safety testing.

Combined Irradiation Test Matrix

Temperature	End of Life Burnup (% FIMA)		
	Low (4)	Medium (6)	High/Margin (11)
Low Operating			12 pebbles Russia
High Operating	4 pebbles South Africa	4 pebbles South Africa 2 to 4 pebbles US	8 to 10 pebbles US
Margin (High Oper. + 100°C)			2 pebbles US

Pre-Demonstration Testing

Facility Location	# Pebbles	Test Temperature (°C)	Comments
Pre-production Fuel			
South Africa	3	1600	
Russia	3	1600	
Archived German Fuel			
US	1	1600	
	1	1700	Safety margin test
	1	1800	Safety margin test

Demonstration Safety Testing

Facility Location	# Pebbles	Test Temperature (°C)	Comments
Production Fuel - Demonstration Portion of Qualification Program			
South Africa	3	1600	4 % FIMA
	3	1600	6 % FIMA
Russia	11	1600	Statistically significant quantity of fuel.

Demonstration Safety Margin Testing

Facility Location	# Pebbles	Test Temperature (°C)	Comments
Production Fuel - Margin Portion of Qualification Program			
US	2	1600	Supplement Russian statistics. Includes fluence irradiation margin.
	1	1600	High temperature irradiation margin
	2	1700	Safety margin test
	1-2	1700	Safety margin test. Medium irradiation burnup
	2	1800	Safety margin test
	1-2	1800	Safety margin test. Medium irradiation burnup

Safety Test Matrix

Number of Tested Pebbles

Temperature °C	Moderate Burnup (~ 4 - 6% FIMA)	High Burnup (~ 11 % FIMA)
1600	3 South Africa @ 4% 3 South Africa @ 6%	3 Pre-Prod South Africa 3 Pre-Prod Russia 11 Russia 1 German 1 US high temperature margin 2 US (includes fluence margin)
1700	1-2 US	2 US 1 German
1800	1-2 US	2 US 1 German

Facility Location	# Pebbles	PIE Comments
Pre-production Fuel		
South Africa	2	One pre and one post safety test
Russia	2	One pre and one post safety test
Archived German Fuel		
US	1	One pre safety test
Production Fuel - Demonstration Portion of Qualification Program		
South Africa	2	4% FIMA - one pre and one post safety test
	2	6% FIMA - one pre and one post safety test
Russia	3	One pre and two post safety test
Production Fuel - Margin Portion of Qualification Program		
US	2	High Temp Margin - one pre and one post safety test
	1	Fluence Margin - one pre safety test (contingent on Hi Temp Margin)
	3	Post 1600, 1700 & 1800 safety tests (includes fluence margin)

- ◆ Describe the Proposed US Pebble Bed Modular Reactor (PBMR) Fuel Qualification Test Program
- ◆ Describe the Proposed International PBMR Fuel Qualification Test Program
- ◆ Discuss the Role of Existing International Fuel Test Data in Establishing the Integrated (i.e. US and International) Fuel Qualification Test Program